ULTRARELATIVISTIC HEAVY ION COLLISIONS: EXPLORING THE PHASE DIAGRAM OF QCD

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ABSTRACT. I present the motivation for studying nuclear collisions at ultrarelativistic energies which is to map the phase diagram of strongly interacting matter under very extreme conditions. The relevant experimental efforts are overviewed and problems in connecting observables with physics of the hot and dense matter are pointed out. I review the current highlights of the experimental programme: excitation functions of various quantities from the SPS which suggest a possibility of the onset of deconfinement, and the evidence of deconfined perfect fluid at RHIC.

THE PHASE DIAGRAM OF QCD

Phase diagram is graphical representation of the qualitative properties of *bulk* matter and of the conditions under which these properties change. Microscopically, the bulk properties result from the underlying interaction between constituents of the material. This also gives typical energy or temperature scales at which phase transitions would happen.

All properties of materials we usually deal with are due to electromagnetic interaction. Let us take water as an example. Boiling and condensing is connected with rearranging bonds between the molecules, so intermolecular van der Waals interaction gives the typical energy scale, which is of order 10^{-2} eV per molecule. By using typical molecular densities one can get an estimate for critical energy density and temperature.

At somewhat higher energy the electrically neutral atoms break up into positively charged ions and electrons. This results in plasma phase. The typical ionisation energy of an atom is of the order of electronvolt, thus about a factor 100 higher temperature than for boiling would be expected.

We can ask if the strong interaction leads to analogic phase transitions. Strong interaction acts on entities with colour charge; the elementary participants are quarks and gluons. Similarly to electromagnetic interaction which acts also between electrically neutral atoms and molecules via van der Waals forces, there is strong interaction between colourless hadrons, e.g. nucleons within a nucleus. Nuclear matter is held together by strong interaction.

The typical energy scale of strong interaction between nucleons in a nucleus shows up as the binding energy. In analogy to phase transition from liquid water to vapor known from everyday life, it turns out that there is a first-order "liquid–gas" phase transition in nuclear matter [1, 2]. The typical temperature is of order of few MeV[1].

Is there a strong interaction analogy to electromagnetic plasma phase with free charges? This appears more problematic: while electric charges can exist alone in vacuum, colour charges *cannot*. They always must be bound together within a colourless object. This property of quarks as carriers of colour charge is called *confinement*. Nevertheless, if the energy density is large enough, loosely speaking if the colour charges are packed together very densely, the quarks may not be anymore bound to hadrons but can freely roam over the whole region occupied by all quarks together [3]. Such a system is labeled *"quark-gluon plasma" (QGP)*.

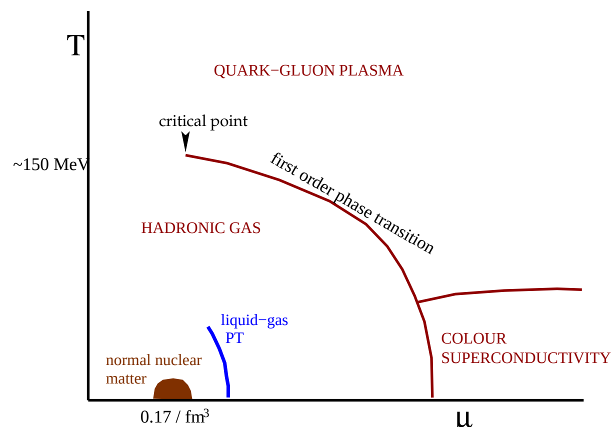

Fig. 1. Schematic view of the phase diagram of nuclear matter as a function of baryochemical potential and the temperature. Note that there are no scales put on the axes.

In principle, the phase diagram is determined by the Lagrangian of underlying interaction. However, in case of the QCD Lagrangian it is technically too complicated to calculate from the first principles, yet. Its structure (Fig. 1) is qualitatively and to certain level quantitatively known from effective theories and numerical simulations. The phase diagram is shown as characterised by the temperature T and baryochemical potential. Baryochemical potential is a measure of *net* baryon density. By changing temperature not only typical momentum of quanta varies but also the densities of baryons *and* antibaryons. We must realise that the typical energy scales in this phase diagram are large, and relativistic effects of particle creation may appear. Thus the particle numbers are not conserved; what is conserved are quantum numbers like baryon number.

At moderately high net baryon density there is the line of first-order liquid-gas phase transition. Farther to asymptotically high baryochemical potential while still at rather low temperature we find the regime of colour superconductivity [4]. This is an analogue to regular superconductivity which appears if there is arbitrarily

[1] Here I use natural system of units where Boltzmann constant $k_B = 1$ as well as $\hbar = c = 1$. Temperature in SI units is obtained by expressing T first in Joules and then dividing by k_B.

weak *attractive* interaction between fermions on Fermi surface. Here, that role is played by certain channels of strong interaction. There are several different phases of colour superconductor, but we shall not go in such details here. Due to the low temperature required, such phase is not produced in nuclear collisions. It might be present in neutron stars, as they are rather cool: only some billion Kelvin. (If you think that this is hot, read below.) Still, there is no clear observational evidence for colour superconductor in a neutron star so far [5].

The regime I want to focus on is that of high temperature. We see in Fig. 1 that at high temperature the plasma phase is expected. The equation of state at vanishing *net* baryon density can be calculated numerically in so-called *lattice QCD* approach [6]. Such calculations indicate that at temperature 173±15 MeV the energy density changes as a function of temperature dramatically but smoothly (Fig. 2). In SI units

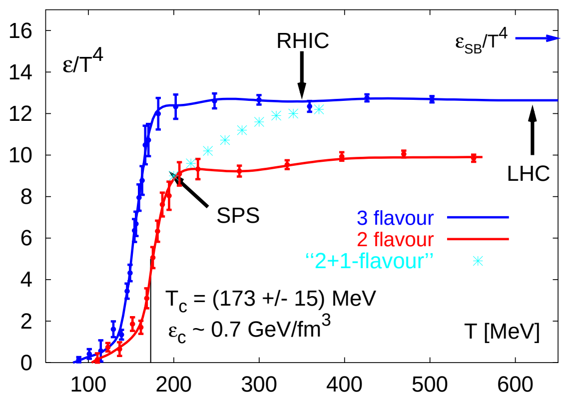

Fig. 2. The energy density normalised by T^4 as a function of temperature from lattice QCD. Simulations with 2 and 3 light quark flavours and with 2 light and one heavy flavour are presented. Labels show the energy densities reached at various accelerators. Figure from [6].

this temperature is about $2 \cdot 10^{12}$ K, which is about 100,000 times hotter than in the centre of the Sun! Two phase transitions happen here: confinement vanishes and chiral symmetry is restored. The former is observed in the simulation as a change of quark-quark potential from linear rise to an asymptotically constant value at large distances; the latter as vanishing of vacuum expectation value of chiral condensate $\langle\bar{\psi}\psi\rangle$.

At large enough non-zero net baryon density first order phase transition appears. The critical line ends in a critical point of second-order phase transition. Exact position of this point is of fundamental interest, although so far there are only calculations based on effective theories or rather unreliable estimates from lattice QCD [7, 8].

CREATING EXTREME CONDITIONS

Have such extreme conditions ever been realised in nature? Can we create them artificially? The answer to both questions is positive.

They existed in early Universe which evolved from a very hot and dense beginning through continuous expanding and cooling. The relation between time and temperature in the early phase was

$$\frac{1}{t^2} = g_* \frac{4\pi^4}{90} \frac{k_B^4 T^4}{\hbar^2 c^4 M_{\mathrm{Pl}}^2}\,, \tag{1}$$

where $M_{\mathrm{Pl}} = \sqrt{\hbar c/G_N}$ is the Planck mass and g_* is the effective number of degrees of freedom (loosely speaking, how many different particle species contribute to the energy density). According to this relation, temperature around 150–200 MeV was reached at time 10–100 microseconds after the Big Bang. This is the time when hadrons were born.

The amazing thing is that we can re-create a small "early Universe" in the lab and study "Little Bangs"! This is done with the help of ultrarelativistic nuclear collisions. By colliding large nuclei energy is converted into new quanta with large typical momentum. At the same time the system is large enough so that we can have bulk matter consisting of many interacting constituents. At sufficient collision energy the energy density within the system will reach up to the regime of QGP.

We have to realise that the colliding nuclei contain only baryons and no antibaryons, thus always matter with positive net baryon density is created. The higher the collision energy, the more secondary particles can be created. Among created particles there are as many baryons as antibaryons and so the ratio of baryons to antibaryons becomes smaller at higher collision energies. Consequently, the baryochemical potential decreases.

Hence, nuclear collisions at various energies can map various regions of the phase diagram. Unfortunately, such collisions create rapidly evolving systems—so-called fireballs—which makes it rather complicated to study the generated matter. Let us have a flash view of the evolution of fireball (Fig. 3).

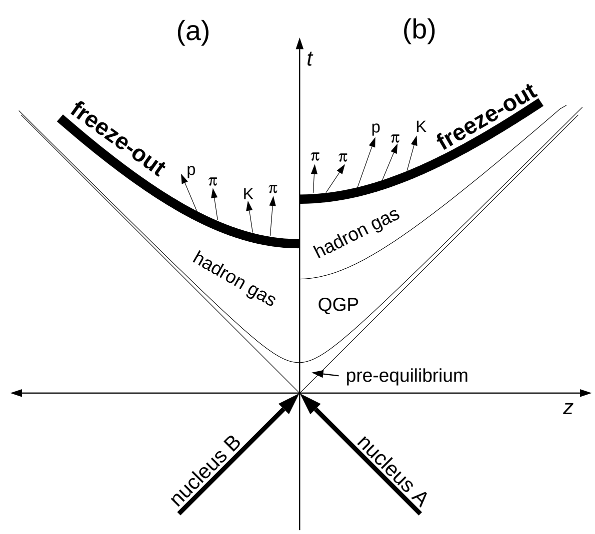

Fig. 3. The space-time diagram of longitudinal coordinate and time of the evolution of fireball (a) without and (b) with the production of quark-gluon plasma.

1. Colliding nuclei have relativistic energy, so before the collision they appear in the centre of mass system Lorentz contracted. The factor γ spans

from about 4 (at lowest SPS energy) up to 100 at RHIC and even more than 2000 at the LHC.

2. If two nuclei collide at high energy, the incident nucleons and/or partons tend to continue their longitudinal motion while being just slowed down somewhat. After they have passed through each other, the energy they have lost converts into new quanta in the region between the receding original nucleons/partons. Just after the collision the energy density of this system is maximum and the matter could find itself in the deconfined phase, if it is high enough.

3. The longitudinal motion continues and thus the system expands longitudinally. Consequently, it cools down. Due to inner pressure also transverse expansion builds up which accelerates the cooling process. Hence, even if the matter was in QGP phase initially, eventually it changes to hadronic phase. This may happen via first-order phase transition in the part of the phase diagram at higher baryochemical potential or via rapid crossover.

4. In any case, the fireball thus ends up in a hadronic phase where is still expands very fast.

5. Eventually, the density of the system becomes so low that no more rescattering between its constituents appear and momenta of hadrons freeze-out. These are the momenta observed in detectors. It is important to realise that *hadrons* are observed and not quarks or gluons.

This scenario runs very quickly. From the initial impact until the freeze-out it lasts about 10 fm/c or more[2]. Unfortunately, we are most interested in studying the hottest and densest phase of matter, but we observe hadrons escaping from the less excited hadronic gas. The main technical problem in this field is thus relating observable quantities with the properties of early hot state of matter.

Before addressing this problem, let me list the existing, recent, and forthcoming experimental facilities devoted to this kind of experiments. For better overview, they are listed in Table 1. Baseline in many observed effects has been provided by the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory (BNL). This machine is currently used as preaccelerator for RHIC (to be mentioned later). Up until recently, experiments have been performed at CERN's Super Proton Synchrotron (SPS) which accelerated nuclei up to the size of lead. These brought interesting results which could indicate the onset of quark-gluon plasma production in this energy region. Currently, world's strongest heavy ion accelerator is Relativistic Heavy Ion Collider (RHIC), where strongly interacting QGP behaving like a perfect fluid has been discovered. In less than a year from now the Large Hadron Collider (LHC) at CERN will be commissioned. Heavy ion studies—in particular with the dedicated detector ALICE—are planned at this machine among others. In 2014 completion of the Facility for Antiproton and Ion Research (FAIR) of the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt is scheduled, which will deliver high luminosity ion beams with energies up to 34 GeV per nucleon for fixed target experiments.

In the following we shall mainly talk about results from experiments performed with lead or gold beams. There were experiments with smaller nuclei, as well (In, Cu, S, O, . . .) in order to gain better systematics of various observables.

TAB. 1. Overview of accelerators used for ultrarelativistic heavy ion studies. I list the maximum energy per participating nucleon in the nucleon-nucleon centre of mass system and whether the setup is fix target experiments or it is a collider.

machine	lab	$\sqrt{s_{NN}^{\max}}$	target or collider
recent			
AGS	BNL	4.8 GeV	target
SPS	CERN	17 GeV	target
present			
RHIC	BNL	200 GeV	collider
forthcoming			
LHC	CERN	5500 GeV	collider
FAIR	GSI	8 GeV	target

FREEZE-OUT STATE: THE GROSS PICTURE

The early hot phase of the collision is not observable directly. There are basically two approaches which can be used in order to learn about it.

1. By studying momentum distributions of low p_t hadrons one can extract information about the state of the fireball at the time of its breakup. This state can be reconstructed and one can deduce the evolution of the fireball which could have lead to it. At least, this method can discriminate theoretical scenarios which lead to the wrong final state.

2. Probes which are produced early and manage to escape the fireball carry direct information about the hot matter. These are e.g. particles which interact only electromagnetically, like photons and (di)leptons. Recently, hard jets have provided very clean probe of the matter, which we shall discuss below.

Let us first have a look at what hadrons tell us about the final state.

It is interesting to analyse their chemical composition. This means that we study how many hadrons of different sorts are there among the observed particles. Interestingly, it turns out that the chemical composition can be very reasonably described by chemical

[2] The time unit fm/c is given by the time it takes for the light to pass the typical size of proton, which is 1 femtometre (called also fermi). This is the typical time scale in high energy physics. In SI it corresponds to about $3 \cdot 10^{-24}$ s.

equilibrium characterised by some value of temperature and baryochemical potential. Moreover, the values of temperature and chemical potential inferred for all collision energies lay on a well defined curve in the T–μ plane (Fig. 4) [9]. Results for RHIC and higher

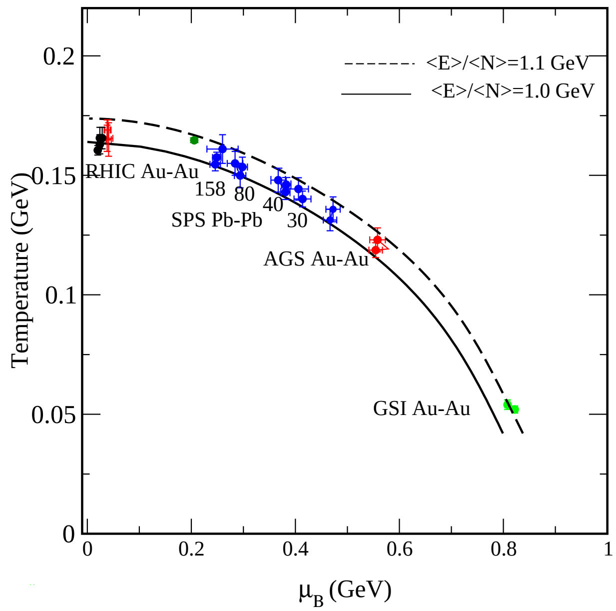

Fig. 4. Temperatures and baryochemical potentials extracted from fits to chemical compositions of hadrons produced in nuclear collisions at various energies. Figure taken from [9].

SPS energies seem to coincide with the region of rapid crossover from hadronic to partonic system and thus suggest that the abundances are fixed through the process of hadronisation. Chemical freeze-out at lower SPS energies, about 6 to 10 GeV per nucleon in the centre of mass system, might be close to the critical point of the phase diagram, though the precise position of this point is unknown, yet [8]. This gives the first hint about regions of phase diagram which can be explored using different facilities: RHIC and LHC will look at hot matter at small baryochemical potential likely undergoing a smooth crossover to hadronic phase. On the other hand, SPS and the future FAIR can search for the line of first order phase transition and the critical point.

From single-particle momentum spectra and momentum correlations we know that the fireball expands transversely rather fast [10, 11]. In a transversely expanding fireball transverse momentum spectra are blueshifted due to Doppler effect. The inverse exponential slope in non-relativistic approximation is given as [12]

$$T_* = T + m\langle v_t\rangle^2\,, \quad \text{where } \frac{dN}{p_t\,dp_t} \propto \exp\left(-\frac{p_t}{T_*}\right)\,. \quad (2)$$

Thus from spectra of several identified species (with different masses) we can extract the average transverse collective expansion velocity $\langle v_t\rangle$. In central collisions at RHIC it reaches up to $0.6c$ [11].

This figure is also supported by momentum correlations. They measure primarily the size of the emitting region. With rather small variation with collision energy in central Pb+Pb and Au+Au collisions the emitting fireball is about twice as big transversely as the original nucleus! The average momentum dependence of correlation functions is also consistent with strong transverse expansion [13, 14]. Conclusion is that we do observe *collectively behaving matter* and not just a bunch of independent nucleon-nucleon collisions and that there is strong pressure in the early phase of the collision.

PERFECT FLUID AT RHIC

Interesting results have been observed in non-central collisions. Here, the two nuclei collide so that the reaction zone is not azimuthally symmetric but rather has elliptic shape with shorter size in direction of the impact parameter. This initial shape anisotropy is translated to an anisotropy in transverse momentum spectra: more particles are produced in the direction of impact parameter. This is quantitatively expressed by Fourier decomposition of the spectrum

$$\frac{d^3N}{p_t\,dp_t\,dy\,d\phi} = \frac{1}{2\pi}\,\frac{d^2N}{p_t\,dp_t\,dy} \times (1 + 2v_2(p_t, y)\cos(\phi-\phi_r) + \dots) \quad (3)$$

(other terms of the decomposition vanish by symmetry at midrapidity, ϕ_r is the azimuthal angle of impact parameter). The second-order coefficient v_2 is called *elliptic flow*.

Momentum anisotropy measured by the elliptic flow is very sensitive probe of conditions in the early hot phase. Data indicate that more transverse flow is produced in the direction of impact parameter than perpendicularly to it. This has natural explanation in hydrodynamics. Flow results from pressure gradients. The smaller size of the reaction zone in the direction of impact parameter implies larger pressure gradients and more flow. This mechanism of generating flow anisotropy vanishes with time as the fireball becomes azimuthally symmetric through expansion and so large flow anisotropy must be generated in the earliest phase.

At RHIC, ideal hydrodynamics describes the transverse expansion and transverse momentum spectra (almost) perfectly [15]. (It only breaks for about 1% of all produced particles with high p_t.) This has not been so at lower collision energies like SPS. Technically, hydrodynamics consists of solving conservation laws and the equation of state. The simulation has been tuned on description of central collisions, i.e., the prescription for determining initial conditions has been fixed there in such a way that spectra were reproduced. Then, without any other tuning elliptic flow in non-central collisions has been successfully predicted, as well [15]. It should be stressed that the model was successful *only* if QGP phase was assumed during the early hot period of fireball evolution!

Recall that data were reproduced with *ideal* hydrodynamics, i.e. with vanishing viscosity. Different simulations with a kinetic model have shown that the mean free path must be extremely short, otherwise the simulation would fall below the measured v_2 [16]. Recall

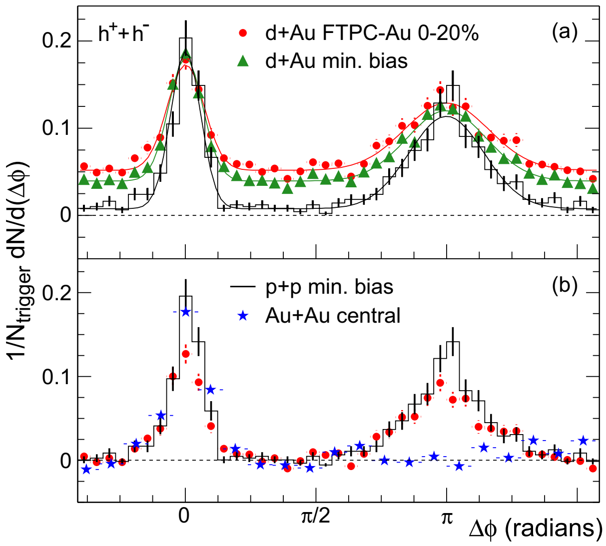

Fig. 5. Azimuthal correlation function of high p_t particles in pp, d+Au, and Au+Au collisions at $\sqrt{s} = 200\,A$GeV. Angle 0 is oriented in direction of a high p_t jet trigger particle. Figure taken from [21].

that in a kinetic approach shear viscosity grows with the mean free path because momentum can be transferred to larger distances. It has also been shown that "viscous" corrections of the elliptic flow just due to modifications of locally thermal distribution are large and always decrease v_2 [17]. The conclusion is that the dimensionless[3] ratio of shear viscosity to entropy density η/s must be very small. Such a small viscosity is consistent with the picture of plasma with *strongly interacting* colour charges [18], because weakly interacting gas would have long mean free path and larger viscosity. Calculations indicate that just above the critical temperature the value of η/s is as small 0.2 [19, 20]. For comparison, the corresponding value for water at normal conditions would be of order[4] 10^3. In fact, the strongly interacting quark-gluon plasma is the most perfect liquid known.

DECONFINEMENT AT RHIC

The previous section indicated that matter produced at RHIC is deconfined. There is another spectacular demonstration of this: the jet quenching.

Jets are well known in high-energy collisions of simpler systems. For example, in proton-proton collisions two partons from incoming protons can exchange large momentum and secondary particles are produced in two rather focused showers around the leading struck out partons. Due to momentum conservation, jets can never be produced alone. Most often, there is one associated jet in the opposite direction, though in some cases three or more associated jets can appear and rarely even counterbalancing photon or lepton is emitted.

The STAR collaboration at RHIC has studied azimuthal correlations of high p_t particles associated with jets (Fig. 5) [21]. In proton-proton and deuteron-gold collisions they found indeed that jets were produced in pairs separated by 180° in azimuthal angle. However, in central Au+Au collisions the associated jet vanished (stars in Fig. 5). Since momentum conservation still holds, the associated jet must have been produced but the leading particle has been completely slowed down when traversing the matter of the fireball. This is a signature of large energy loss of leading jet parton which is only possible in a medium with high density of colour charge, such as QGP.

Recently, more detailed studies showed that jets with very large transverse momentum poke out through the medium [22]. This opens possibility to study the energy loss of leading partons quantitatively and make conclusions about the density of early hot phase.

THE ONSET OF DECONFINEMENT

If QGP is produced at RHIC, what is the *minimum* collision energy at which deconfinement sets in? In order to answer this question one would study excitation functions, i.e. dependences of various quantities on the collision energy.

One example is shown in Fig. 6 [23]. The ratio of

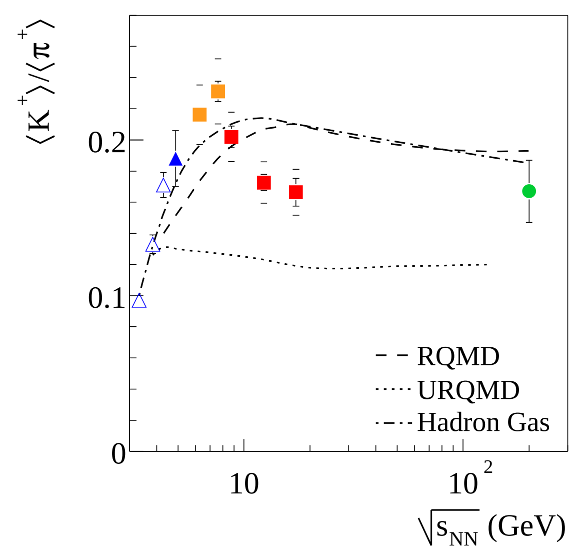

Fig. 6. Excitation function of the ratio of multiplicities of positively charged kaons to pions. Curves present results of various model calculations. Data of the NA49 Collaboration, figure taken from [23].

multiplicities of positively charged kaons to pions first rapidly grows as a function of collision energy. It peaks around $\sqrt{s} \approx 7\,A$GeV drops down a little and then it levels off. This interesting non-monotonic structure—which has been dubbed "the horn"—gives a first hint that something may be happening here. In addition to this, in the same energy region where the horn of Fig. 6 drops to the right one observes a plateau in the excitation function of the mean p_t of kaons. Finally, the number of produced pions per participating nucleon changes its slope as a function of collision energy just

[3]This ratio is dimensionless in natural units. In SI, dimension of viscosity is $[\eta] = \mathrm{N\cdot s\cdot m^{-2}}$ and that of entropy density is $[s] = \mathrm{J\cdot K^{-1}\cdot m^{-3}}$, so $[\eta/s] = \mathrm{K\cdot s} = [\hbar/k_B]$.

[4]I should say that at higher temperature η/s of water can be as small as about 2, but even this is still much bigger than QGP.

at the same place as the horn [23].

These observations are successfully interpreted in framework of so-called Statistical Model of Early Stage [24] which assumes the onset of deconfinement where the horn appears. However, if indeed QGP is produced here, then no hadronic model should be able to describe all data. Thus it is important to play *Advocatus Diaboli* and test hadronic models by comparing their predictions with data. Indeed, most of them fail in reproducing these excitation functions [25, 26, 27]. Recently, we constructed hadronic kinetic model [28] which reproduced the horn of Fig. 6. It remains to test this model on other pieces of data before it can be confirmed or ruled out.

CONCLUSIONS

Let me summarise my selection of current highlights of ultrarelativistic heavy ion programme.

1. QGP may be produced at lowest energies studied at the SPS. Careful investigations, also employing the new FAIR machine, are necessary in order to confirm this.

2. Jet quenching at RHIC implies that we have matter which eats jets. The only known medium able to do this is quark-gluon plasma.

3. Elliptic flow at RHIC is as large as it can possibly be in perfect fluid and so the viscosity of QGP is tremendously small. This is consistent with the regime of strongly interacting QGP at temperatures just above T_c.

The Large Hadron Collider to be commissioned next year will shift the frontiers in points 2 and 3. Due to higher incident energy, jets which probe the early hot matter will be produced copiously. At the larger initial temperature the medium could find itself in a not-so-strongly interacting regime as the strong coupling decreases for interactions at large momentum scale. This would lead to larger viscosity and it would be interesting to observe a corresponding decrease of elliptic flow. Such an observation would nicely extend our knowledge of the QCD phase diagram.

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